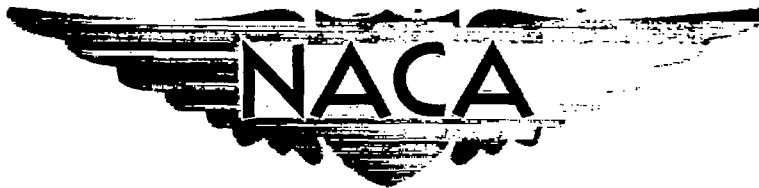


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# RESEARCH MEMORANDUM

INVESTIGATION OF TURBINES FOR DRIVING SUPERSONIC COMPRESSORS

II - PERFORMANCE OF FIRST CONFIGURATION WITH 2.2-PERCENT

REDUCTION IN NOZZLE FLOW AREA

By Warner L. Stewart, Harold J. Schum and Robert Y. Wong

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Cleveland, Ohio

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YRN-121 Date Oct. 14, 1957

ANT 11-15-57

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## NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

July 22, 1952

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RESEARCH MEMORANDUM

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## SUMMARY

The experimental performance of a modified turbine for driving a supersonic compressor is presented and compared with that of the original configuration in order to illustrate the effect of small changes in the ratio of nozzle-throat area to rotor-throat area on the performance of turbines designed to operate with both blade rows close to choking.

The turbine modification consisted of a 2.2-percent reduction in nozzle-throat area by decreasing the nozzle-exit blade angle  $1^\circ$ . The experimental performance indicates that, at design speed, design specific work was obtained at the design total-pressure ratio of 2.19 and an adiabatic efficiency of 0.80, whereas in the original configuration the turbine limiting-loading point was reached at a specific work output just below that of design. At design total-pressure ratio, a 3-point increase in adiabatic efficiency was obtained over that of the initial configuration. This increase resulted from operation that was further removed from the turbine limiting-loading point which, in turn, reduced the losses at the rotor exit. Design specific work was obtained because of increased nozzle-exit tangential velocities; however, the rotor still limited the flow so that negative turbine-exit tangential velocities were required to obtain the required specific work output. A reduction in weight flow of only 1.5 percent could be attributed to decreased total conditions relative to the rotor. On the basis of the results of this investigation, it is concluded that the ratio of nozzle-throat area to rotor-throat area becomes especially critical in the design of turbines such as those designed to drive high-speed, high-specific-weight-flow compressors where the turbine nozzles and rotor are both very close to choking.

## INTRODUCTION

As part of a program to study the aerodynamic problems associated with turbines designed to drive high-speed, high-specific-weight-flow compressors, an investigation of turbines for driving a particular supersonic compressor is being conducted at the NACA Lewis laboratory. The design and cold-air investigation of the first turbine configuration has been completed (reference 1). The high-speed, high-specific-weight-flow characteristics of the compressor resulted in a severe stress problem in the turbine-rotor design. In order to reduce the stress to a practical value, the absolute Mach number leaving the turbine was made high, resulting in a turbine design in which both the rotor and the nozzle operated very close to choking. The performance of the turbine of reference 1 indicated that the rotor limited the weight flow to 95 percent of that of design which resulted in nozzle-exit tangential velocities considerably less than design. This resulted in a specific work output slightly less than that of design. Reference 1 indicated that an improvement in the turbine efficiency could be obtained by increasing the nozzle-exit tangential velocities. As stated in reference 1, the simplest means of increasing these velocities would be to reduce the nozzle-throat area. An additional small reduction in air weight flow, however, would be expected because of the decreased total conditions relative to the rotor.

The subject report illustrates the effect of small changes in the ratio of nozzle-throat area to rotor-throat area on the performance of turbines designed to operate with both the nozzle and the rotor blades close to choking. The experimental performance of the cold-air turbine of reference 1 with a 2.2-percent reduction in nozzle-throat area is presented herein and compared with that of the original configuration. Herein the original configuration will be referred to as 1A, and the modified configuration will be referred to as 1B.

## SYMBOLS

The following symbols are used in this report:

h	specific enthalpy, Btu/lb
N	rotative speed, rpm
p	absolute pressure, lb/sq ft
r	radius, ft
T	absolute temperature, °R
U	blade velocity, ft/sec

w weight-flow rate, lb/sec

$\gamma$  ratio of specific heats

$\delta$  ratio of inlet-air pressure to NACA standard sea-level pressure,  
 $p_1'/p^*$

$\epsilon$  function of  $\gamma, \frac{r^*}{r} \left[ \frac{\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}}}{\left(\frac{\gamma^*+1}{2}\right)^{\frac{\gamma^*}{\gamma^*-1}}} \right]$

$\eta$  adiabatic efficiency defined as the ratio of turbine work based on temperature measurements to ideal turbine work based on inlet total conditions, and outlet total pressure consisting of the static pressure plus the pressure corresponding to the axial component of velocity

$\theta_{cr}$  squared ratio of critical velocity at turbine inlet to critical velocity at NACA standard sea-level temperature,  $(V_{cr}/V_{cr}^*)^2$

#### Subscripts:

av average

t rotor tip or outer radius

1 measuring station upstream of nozzles

2 measuring station at nozzle outlet, rotor inlet

3 measuring station downstream of rotor

4 measuring station in outlet pipe

#### Superscripts:

\* NACA standard conditions

' total state

## TURBINE BLADING MODIFICATION

The turbine blading used in this investigation was the same as that described in reference 1 with the exception of the nozzle-throat area. This flow area was reduced 2.2 percent by changing the nozzle angle  $1^\circ$ . The throat area at the hub and tip were measured before and after the angle change. The two areas were then arithmetically averaged for each setting and these averages compared to obtain the stated reduction. Prior to installation of the rotor, the choking weight flow through the modified nozzle configuration was obtained. The observed weight flow of 14.4 pounds per second represented a 2.7-percent drop from the original-nozzle choking weight flow and approximated the area measurements closely. This weight flow was slightly less than the rotor choking weight flow of configuration 1A which was 14.5 pounds per second as reported in reference 1.

## APPARATUS, INSTRUMENTATION, AND METHODS

The apparatus, the instrumentation, and the methods of calculating the performance parameters used in this investigation were the same as those described in detail in reference 1 with the exception of the aforementioned nozzle flow-angle change and the addition of a honeycomb flow-straightening section in the turbine discharge ducting, approximately 18 inches upstream of the turbine-outlet temperature rake. A diagrammatic sketch of the turbine setup and its various components is shown in figure 1. The straightening section was incorporated in the apparatus in order to reduce the flow angle relative to the thermocouple rake at the turbine-outlet measuring station (station 4, fig. 1). Although the thermocouple rake is considered to be relatively insensitive to yaw, it was felt that the accuracy of the temperature measurements would be improved at off-design operation where the deviation of the flow angle from axial becomes the greatest.

All the turbine performance runs were made in the same manner as those of reference 1. The turbine-inlet temperature and pressure were maintained constant at nominal values of  $135^\circ\text{F}$  and 32 inches of mercury absolute, respectively. The speed was varied from 50 to 130 percent of design speed in even increments of 10 percent. At each speed, the total-pressure ratio across the turbine was varied from the maximum possible (as dictated by the laboratory exhaust facilities) to approximately 1.40. Turbine adiabatic efficiency was based on the ratio of inlet total pressure to outlet total pressure (both defined as the sum of the static pressure and the pressure of the axial component of velocity, see reference 1).

The accuracy of the measured and calculated parameters is estimated to be within the following limits:

Temperature, °F . . . . .	±0.5
Pressure, in. Hg . . . . .	±0.05
Weight flow, percent . . . . .	±1.0
Turbine speed, rpm . . . . .	±20
Efficiency, percent . . . . .	±2.0

These values refer to the absolute accuracy. The reproducibility of the adiabatic efficiency at or near design operating conditions was calculated to be within ±0.6 points.

## RESULTS AND DISCUSSION

Over-all performance. - As discussed in the TURBINE BLADING MODIFICATION section, the nozzle-throat area of configuration 1B was 2.2 percent less than that of configuration 1A. The over-all performance of configuration 1B is illustrated in figure 2. The equivalent specific work  $\Delta h' / \theta_{cr}$  as calculated by the total-temperature measurements is shown as a function of the weight-flow parameter  $\epsilon W N / \delta$  (product of equivalent weight flow and turbine speed) with percent of design speed and total-pressure ratio as parameters. Efficiency contours are also included. The design-equivalent-specific-work and weight-flow parameter used in the turbine design (reference 1) are indicated by point B. Design equivalent specific work and speed are denoted by point A. As indicated by point A, design specific work was obtained at the design total-pressure ratio of 2.19 and at an adiabatic efficiency of 0.80. A comparison of the abscissas shows that 93.5 percent of design weight flow was passed, representing a drop of only 1.5 percent from that of configuration 1A. A peak efficiency region of over 0.85 can be observed around 90 percent of design speed and a total-pressure ratio of 1.7. This peak efficiency did not change in value from configuration 1A but shifted slightly to a region of higher total-pressure ratio (compare with reference 1).

The performance results of configurations 1A and 1B at design speed are presented in figure 3. The variation in equivalent specific work and adiabatic efficiency with total-pressure ratio is shown. It is apparent that for configuration 1B, design specific work was obtained before the turbine limiting-loading point was reached; whereas in configuration 1A, the turbine limiting-loading point was reached just before design specific work was obtained. The turbine limiting-loading point is defined as that point at which further increases in total-pressure ratio result in no additional turbine work output. It can also be noted that at the total-pressure ratio of 2.19 an efficiency increase of approximately 3 points was obtained for configuration 1B over that of configuration 1A. The peak efficiency remained at approximately 0.84

but shifted from a total-pressure ratio of 1.65 obtained in configuration 1A to a total-pressure ratio of 1.85. The turbine design requirements and the results of the experimental investigations of configurations 1A and 1B are summarized in table I.

Choking of rotor. - The total-to-static pressure ratio across the nozzles at the inner and outer walls are shown in figure 4 as a function of the total-pressure ratio across the turbine at design speed. For comparison, the curves for configuration 1A are also included. For configuration 1B, there is no change in total-to-static pressure ratio across the nozzles beyond a total-pressure ratio of 1.8. Thus, the rotor is again choking at this total-pressure ratio; therefore, an increase in total-pressure ratio across the turbine does not affect the rotor inlet conditions. Although both configurations choked at a turbine total-pressure ratio of about 1.80 (fig. 4), the total-to-static pressure ratio across the nozzles at both the inner and outer walls was increased for configuration 1B over that obtained for configuration 1A. Because the nozzle-exit angle was not appreciably changed, the velocities leaving the nozzles were therefore increased with a resultant increase in nozzle-exit tangential velocities.

The design total-to-static pressure ratios across the nozzles at the inner and outer walls (fig. 4) are based on isentropic flow through the nozzles. Because of losses incurred in the nozzles, the total-to-static pressure ratio would have to be slightly higher than shown in order to obtain the design nozzle-exit tangential velocities. A comparison of the design total-to-static pressure ratio with that actually obtained indicates that the nozzle-exit velocities at the tip were close to design, whereas the nozzle-exit tangential velocities at the hub were considerably less than that of design. Even with the higher nozzle-exit tangential velocities, some negative rotor-exit tangential velocities were therefore still required to obtain the design specific work. This is shown in figure 5 where absolute discharge flow angle and temperature-drop ratio surveys are presented for configuration 1B at a total-pressure ratio of 2.18, which is very close to the total-pressure ratio at which design specific work was obtained. The surveys were taken at station 3 (fig. 1). The angle survey indicates considerable negative exit tangential velocities near the inner wall as evidenced by approximately 15° of overturning. The flow angle diminishes toward the outer wall until a small amount of positive exit tangential velocity is indicated by approximately 7° of underturning at the outer wall. The temperature-drop survey indicates a high specific work output over one-half of the blade near the inner wall; the specific work output, however, then decreases considerably near the tip. Hence, although the average specific work output is design, the specific work output near the hub is greater than design and can be attributed to the negative exit tangential velocities in this region.

Analysis of results. - The experimental performance of configuration 1B has indicated that, with a 2.2-percent reduction in nozzle-throat area, a sufficient increase in nozzle exit tangential velocities was obtained so that, at design speed, design specific work was obtained at a total-pressure ratio less than that corresponding to the turbine limiting-loading point. At a total-pressure ratio where design work was obtained, the adiabatic efficiency for configuration 1B increased 3 points over that of configuration 1A (fig. 3). This increase in efficiency resulted from turbine operation that was further removed from the turbine limiting-loading point which, in turn, reduced losses at the rotor exit. Because the rotor limited the flow at design speed and at design total-pressure ratio, the 1.5-percent reduction in rotor choking weight flow can be attributed to the decreased total conditions relative to the rotor entrance which were caused by the increased nozzle-exit tangential velocities.

Because design nozzle-exit tangential velocities were not obtained, negative exit tangential velocities were found necessary in order to obtain the desired average specific work. If the ratio of nozzle-throat area to rotor-throat area could be altered further, an additional increase in efficiency and specific work output would be expected. The nozzle-exit tangential velocities could then be increased more and design specific work would be obtained with less negative turbine-exit tangential velocities. The corresponding total-pressure ratio would then be further removed from the turbine limiting-loading point.

The experimental performance also indicated that a high specific work output could be obtained near the inner wall, whereas the work output near the outer wall was limited. This phenomenon indicates the possibility that the rotor tip reaches limiting loading at total-pressure ratios below the turbine limiting-loading point. From this consideration, a more efficient turbine configuration might be evolved so that an increased work output would be obtained before the limiting loading at the tip would be reached.

#### SUMMARY OF RESULTS

From an investigation of the performance of a turbine designed for driving a supersonic compressor and modified from that of the initial configuration by a reduction in nozzle-throat area of 2.2 percent the following results were obtained:

1. At design speed, design specific work was obtained at the design total-pressure ratio of 2.19 and an efficiency of 0.80; whereas the performance of the initial configuration indicated that the turbine limiting-loading point was reached at a specific work just below design.



2. At design total-pressure ratio, a 3-point increase in adiabatic efficiency was obtained over that of the initial configuration. This increase resulted from turbine operation that was further removed from the turbine limiting-loading point, which, in turn, reduced the losses at the rotor exit.

3. Design specific work was obtained because of increased nozzle-exit tangential velocities; however, the rotor still limited the flow so that negative turbine-exit tangential velocities were required to obtain the required specific work output. The reduction in weight flow of only 1.5 percent could be attributed to decreased total conditions relative to the rotor.

#### CONCLUSION

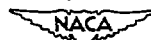
On the basis of the results of the investigation presented herein, the ratio of nozzle-throat area to rotor-throat area is concluded to become especially critical in the design of turbines such as those designed to drive high-speed, high specific-weight-flow compressors where the turbine nozzles and rotor are both very close to choking.

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National Advisory Committee for Aeronautics  
Cleveland, Ohio

#### REFERENCE

1. Stewart, Warner L., Schum, Harold J., and Whitney, Warren J.: Investigation of Turbines for Driving Supersonic Compressors. I - Design and Performance of First Configuration. NACA RM E52C25, 1952.

TABLE I - DESIGN REQUIREMENTS AND EXPERIMENTAL RESULTS  
OF TURBINE FOR DRIVING SUPERSONIC COMPRESSOR



	Design require- ment	Turbine configuration	
		1A	1B
Equivalent weight flow, $\epsilon w \sqrt{\theta_{cr}} / \delta$ , lb/sec	15.2	14.5	14.25
Equivalent tip speed, $U_t / \sqrt{\theta_{cr}}$ , ft/sec	752	752	752
Equivalent specific work, $\Delta h' / \theta_{cr}$ , Btu/lb	20.0	Limiting loading before design work	20.0
Total-pressure ratio, $P_1' / P_3'$	2.19	-----	2.19
Adiabatic efficiency, $\eta$	0.80	-----	0.80

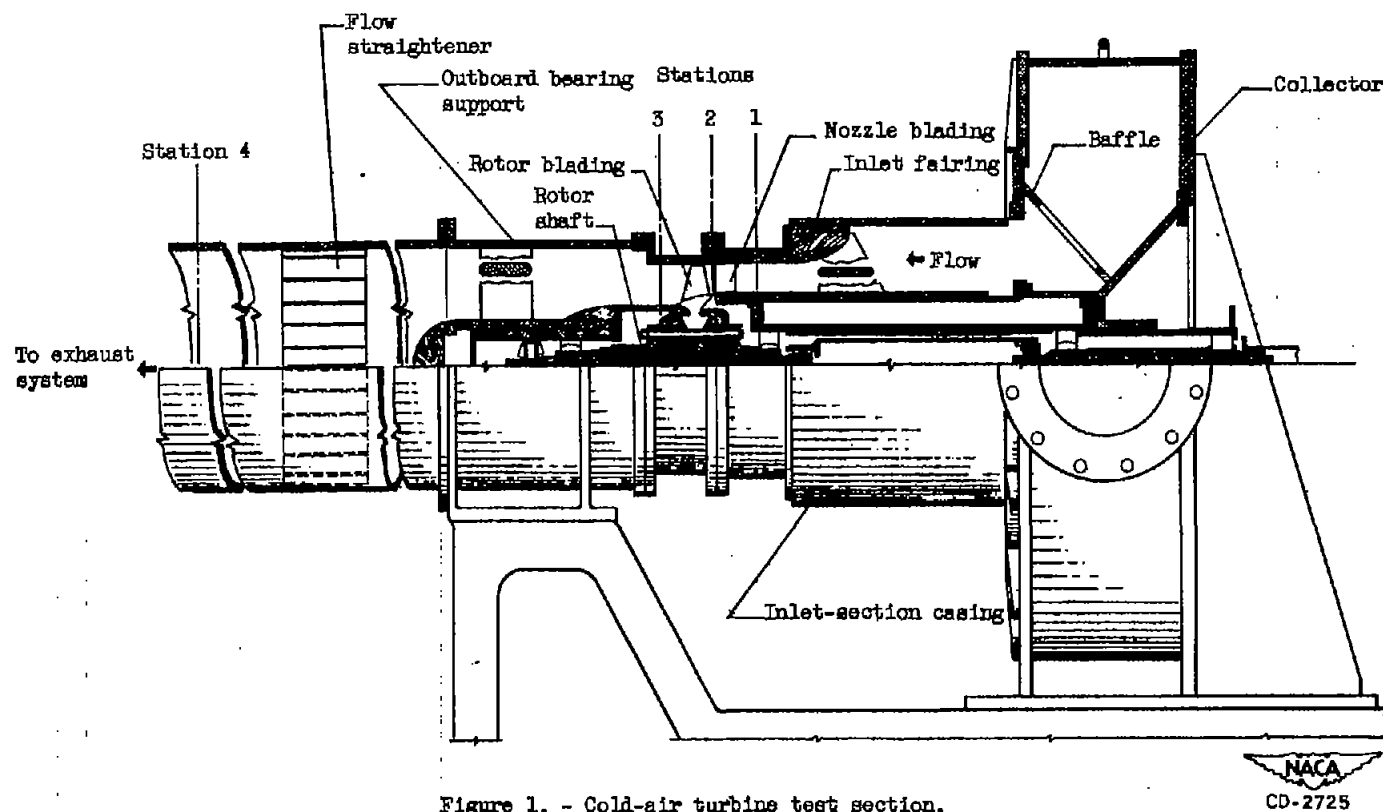


Figure 1. - Cold-air turbine test section.

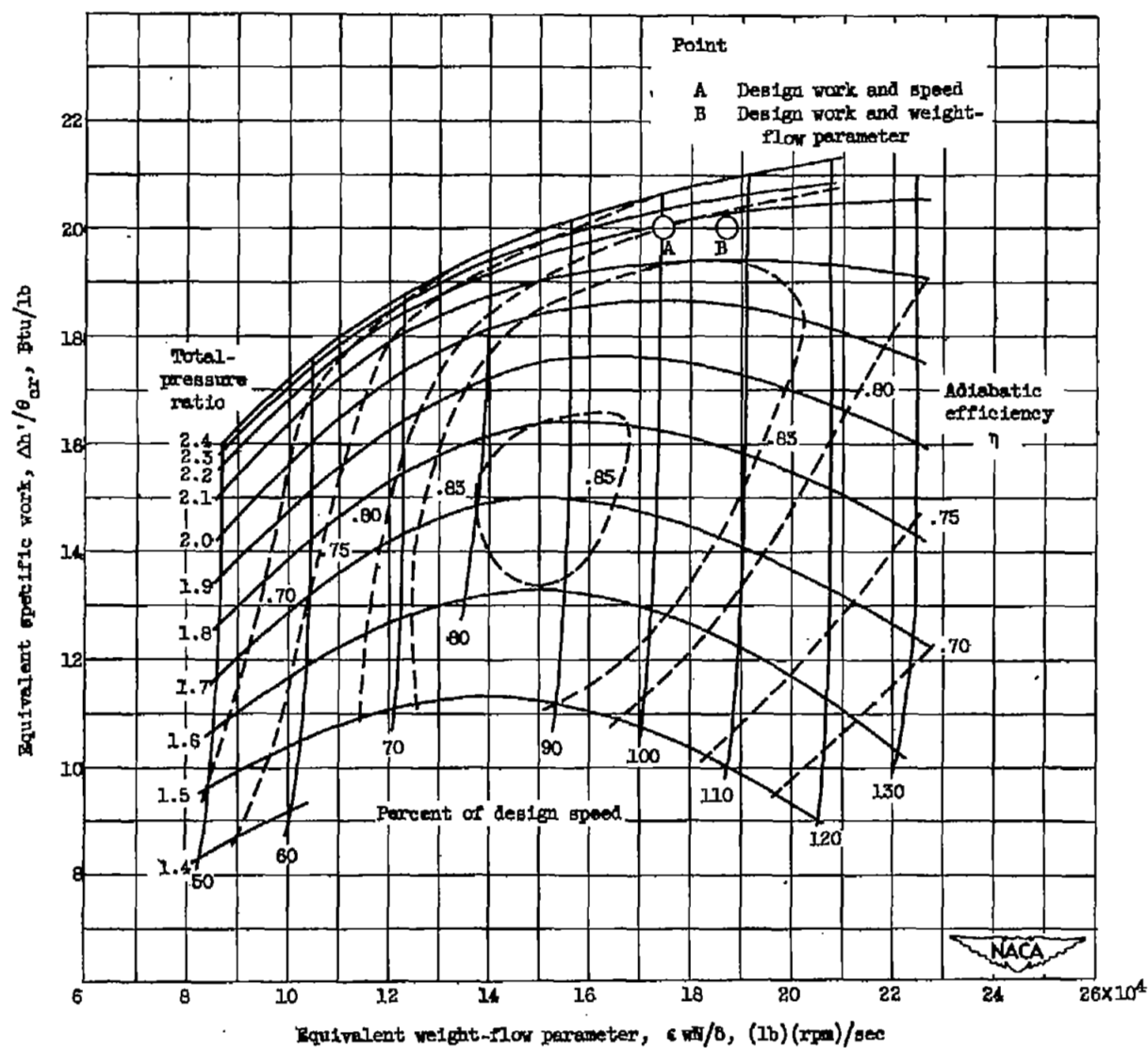


Figure 2. - Over-all performance of turbine configuration 1B.

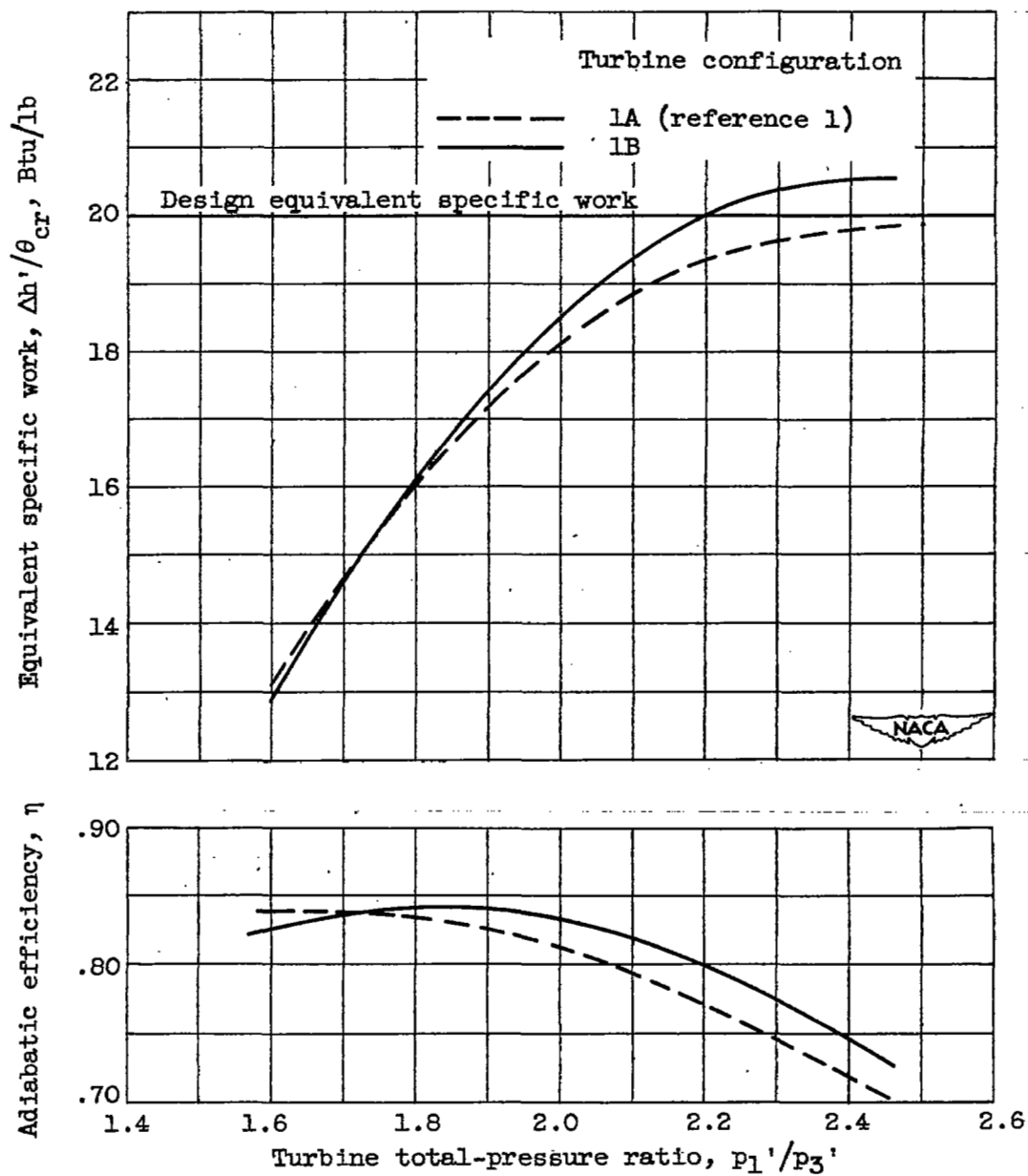


Figure 3. - Variation in equivalent work and efficiency with total-pressure ratio across turbine at design speed.

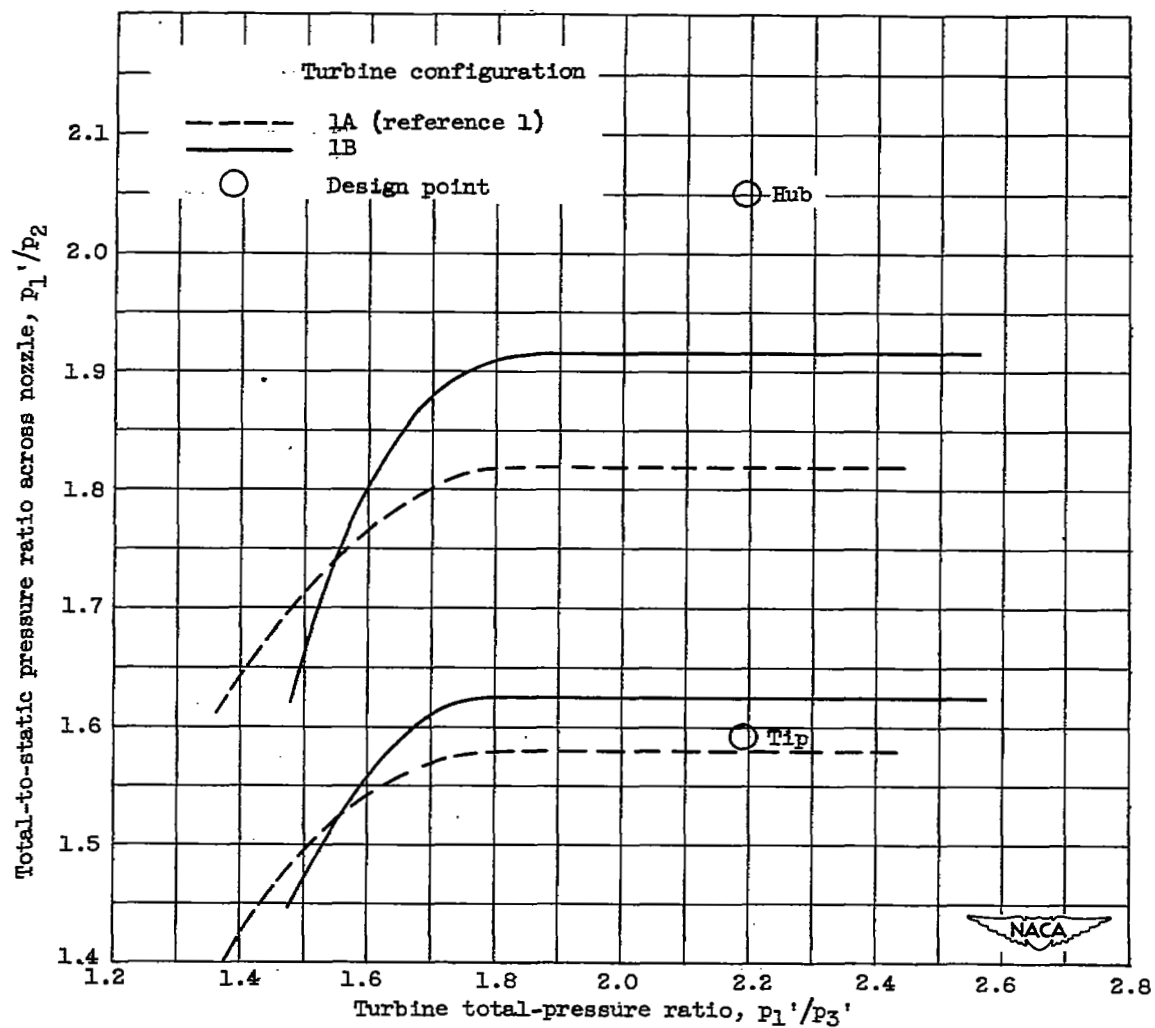


Figure 4. - Effect of total-pressure ratio across turbine on total-to-static pressure ratio across nozzles at design speed.

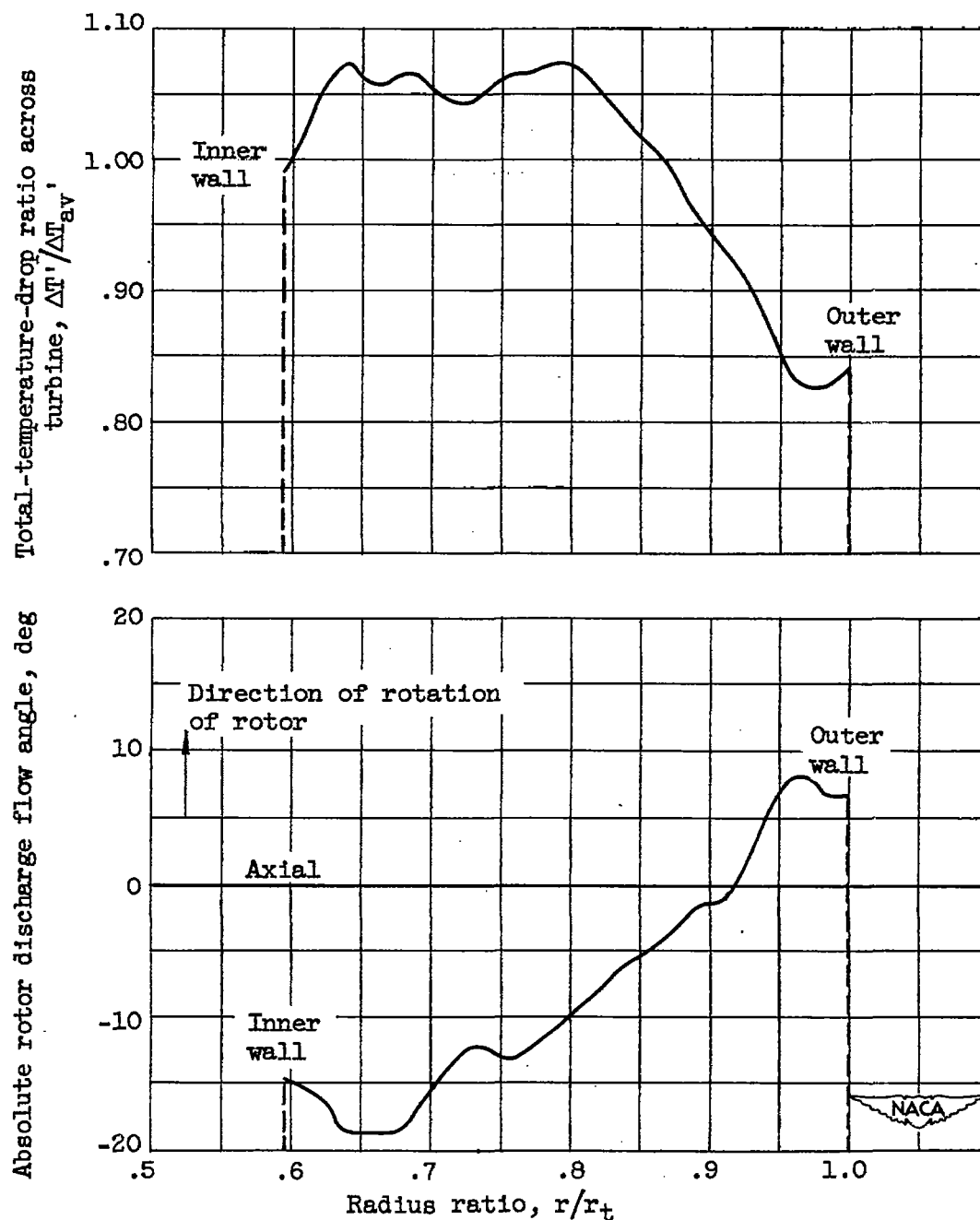


Figure 5. - Variation of rotor discharge flow angle and total-temperature-drop ratio with rotor discharge radius ratio at design speed and total-pressure ratio of 2.18.

# SECURITY INFORMATION

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